

AAS 10-014

AN OVERVIEW OF NASA'S ORBITAL DEBRIS ENVIRONMENT MODEL

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Using updated measurement data, analysis tools, and modeling techniques, the NASA Orbital Debris Program Office has created a new Orbital Debris Environment Model. This model extends the coverage of orbital debris flux throughout the Earth orbit environment, and includes information on the mass density of the debris as well as the uncertainties in the model environment. This paper will give an overview of this model and its implications for spacecraft risk analysis.

INTRODUCTION

Engineering models are tools for estimating the orbital debris populations for use in measurement campaign planning and for spacecraft hazard assessments and design. The models need to be able to provide the user accurate results in a timely fashion. Because of the long lead times in new satellite designs and the multi-year operational life cycle of satellites, the long-term temporal behavior of the debris environment is of interest as well.

Two main constituencies compose the engineering model user community: spacecraft designers and operators, and debris observers. Spacecraft designers need the orbital debris flux as a function of debris size, direction, and relative speed. In addition, they would like information on the debris material type and shape, if possible, to better refine their shielding needs. For observers planning debris observation campaigns, the flux as a function of size and altitude needs to be computed for the observer's location and pointing direction.

Thus, any engineering model must include an accurate assessment of the orbital debris environment at any time, based on model debris populations that closely approximate those actually in space. That means the model orbit distributions must contain all relevant orbit information necessary for the computation of the desired flux values.

ENGINEERING MODEL HISTORY

Engineering models were first assembled for NASA use. Kessler developed the first debris engineering model for the Space Station Program Office. Further models were assembled for the Strategic Defense Initiative Organization and various LEO spacecraft programs and again, the Space Station Program Office.^{1, 2, 3} Each of these models portrayed the environment in terms of curve fits to describe the distributions of large objects (the SSN catalog of objects larger than approximately 10 cm) and small objects (as recorded by the inspection of exposed spacecraft surfaces returned from space). Debris populations in the intermediate size regimes (1 mm to 10

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cm in size) were based on model predictions of satellite breakups rather than on empirical data. There was little data at the time with which to calibrate these models, so the results for some regions and regimes had significant uncertainties. These models were designed to be easily executed by a programmable calculator in a short amount of time. The important effects of inclination distribution and velocity/direction dependencies were handled in a very general way.

The addition of Haystack radar data in the early 1990's gave, for the first time, an accurate assessment of the 1 – 10 cm debris population in low-Earth orbit. In addition, it became clear from the Haystack data that, in some cases, debris in the centimeter size regime showed qualitatively different orbit distributions from the catalogued distributions. ORDEM96 was developed to capture not only the improved centimeter populations, but also the improved knowledge in the distribution of debris in inclination, altitude, and eccentricity.⁴ In addition, improved computer technology allowed for numerical integration of the debris flux equations to obtain better direction/velocity spacecraft flux distributions. This precluded the use of simple formulae for describing spacecraft flux, but the debris populations in ORDEM96 had discrete debris populations that were still described by a set of analytic equations. These discrete debris "families" were each assigned a single value of inclination and eccentricity based on the limited information available and to aid in calculations. The resulting model gave a much higher fidelity directional flux distribution that greatly aided in modifying Space Station shield designs and Space Shuttle operational orientations to minimize debris risks.

By the late 1990s, it became clear from accumulated Haystack radar observations and Shuttle returned surfaces that it was time to update the NASA engineering model. In addition, improvements in computer power and storage made many of the limitations of ORDEM96 no longer necessary. Also, new techniques were developed to extract higher fidelity orbit data from the available data. The resulting engineering model, released in 2000, is called ORDEM2000.⁵ This model defined debris populations at discrete finite element cells around the Earth. These finite cells preserved debris size, spatial density, and horizontal (tangent to the local Earth surface) velocity. Limiting the velocity in this way was an appropriate approximation for a model that only computed fluxes at altitudes below 2000 km.

ORDEM2010

Since the release of ORDEM2000, several important issues have arisen with regard to information desired in an Engineering model. Most important was an increased interest in assessing the uncertainties of the flux calculations. Much of the time and energy in developing the new ORDEM2010 model has gone into trying to accurately estimate these uncertainties.

Another important issue was the desire to include debris shape and material type in any new model. While we have made advances in computing the relative contribution of different material types, the ability to include debris shape information is still quite limited.⁶ Therefore, ORDEM2010 has explicit distributions in mass density for the breakup debris population, but shape is not explicitly calculated in the model.

In addition, new data has allowed us to extend the orbital debris model environment to most of Earth orbit – extending beyond the geosynchronous belt. Extending the environment out of low-Earth orbit adds another complication to the problem. The model now requires information on the radial velocity of the elliptical component of the debris population. This means that for some orbits, the flux can no longer be assumed to be confined to the local horizontal plane.

ORDEM2000 stored debris population information in 6-dimensional finite elements: time (year), size, altitude, latitude, direction, and speed (longitude was assumed to be randomized). ORDEM2010 adds the radial velocity and break down the populations by material type, which

under the ORDEM2000 framework would have resulted in eight dimensions – a very difficult task even with modern computer capabilities.

ORDEM2010 instead stores the debris populations in terms of their orbital parameters, rather than physical spatial density. Assuming randomized ascending nodes and arguments of perigee, the number of dimensions is reduced back to six: perigee, eccentricity, inclination, time, size, and material type. The program trades off storage space against longer computation time. The new model is much slower than previous ORDEM models, but it now computes the numerical integration errors along with propagating the population uncertainties.

Another change is the increase in the number of reference size points from one per decade to two per decade to increase the accuracy of the size interpolation. The size ranges from a minimum of 10 μm to a maximum of 1 meter. In addition, the population is divided into five discrete populations based on material density: RORSAT Sodium-Potassium coolant (0.9 g/cm^3), intact objects (including mission-related debris), and three types of fragmentation debris: low-density (1.4 g/cm^3), medium-density (2.8 g/cm^3), and high-density (8.0 g/cm^3). These three categories implicitly include fragmentation debris from explosions, collisions, surface degradation, and SRM debris. Each of these material density populations has an independent, unique orbital distribution and set of uncertainties associated with it.

DATA

As with ORDEM2000, ORDEM2010 is based as much as possible upon empirical data.^{7,8,9} Small particles less than 1 mm in size are modeled similarly to the populations in ORDEM2000 using primarily Shuttle returned surface data, but with two major differences. First, the orbital distributions of the small particles are predicted using larger debris and intact objects as sources and the particle orbits evolved to generate the orbital distributions of the populations. The model production rates/spatial densities of these populations are then benchmarked to the cratering rate on the Shuttle returned surfaces. These surfaces also supply chemical information on the material breakdown of the on-orbit population as well. Second, the fitting process attempts to propagate the sampling and other uncertainties into the final population estimates.

Populations between 1 mm and 10 cm are estimated using information from the Goldstone and Haystack radars. Actual orbit distributions were formed by statistically fitting the radar cross-section size estimates, the range, and (for Haystack) the Doppler range-rate velocities. Populations simulated by the LEGEND model from historical breakups are used to provide information that cannot be directly estimated from radar observations, such as extrapolating the debris populations into regions with no radar observations (e.g., low-inclination, high-eccentricity populations).¹⁰ In addition, the orbital distributions from LEGEND were used to help bound the statistical radar fits for orbital parameters that were ambiguous or difficult to calculate from radar observations alone (such as the eccentricity distribution of highly elliptical orbits). Again, there was an attempt to accurately propagate the measurement and fitting uncertainties into the population estimates.

Material breakdowns for these intermediate sizes were estimated by analysis of the SOCIT4 ground test results, and by studying the material compositions of satellites.¹¹ As with other parameters, there was an attempt to propagate the uncertainties in these population breakdowns.

For debris and intact larger than 10 cm, data from the U.S. Satellite Catalog maintained by the Department of Defense are used. These represent the objects tracked by the U.S. Space Surveillance Network. The ORDEM2010 populations include estimates of the completeness of the catalog at the 10 cm threshold.

Future populations are estimated by using 100 Monte Carlo runs of LEGEND under the nominal future prediction scenario (including assumptions about future solar activity). This adds another layer of uncertainty in the spread of possible future environments. The future populations (out to the year 2035) thus represent the mean of these 100 Monte Carlo runs.

During the development of ORDEM2010, two unusual breakups occurred – the Chinese anti-satellite test in 2007 and the Iridium-Cosmos collision in 2009. The debris clouds from these two breakups have been explicitly added to the model based on empirical data gathered by the Haystack and Goldstone radars.

Computing the populations in the near-geosynchronous orbit environment (for simplicity, this total region will be termed “GEO”) required some special exceptions. Objects in this region undergo orbit evolution whereby the inclination and ascending nodes are linked, so that the assumption of randomized ascending nodes that was used in low-Earth orbit no longer applies. Therefore, these orbit distributions are treated differently, with an extra parameter to define ascending node.

Note that because of data limitations, the small particle environment (less than 1 mm) is only intended to be complete for low-Earth orbit (below about 2000 km). Because there are elliptical orbits in the model, debris flux can be computed for orbits that visit higher altitudes, but the small particle flux will be incomplete. The populations in the GEO regime are only modeled down to the 10 cm size, so flux calculations in that regime would only be complete down to that size.

FLUX CALCULATIONS AND UNCERTAINTIES

Because ORDEM2010 allows computation of radial velocities, there is a need to describe the flux in terms of two-dimensional directions, as well as in terms of relative speed. This is accomplished by dividing the flux directions of the spacecraft into a two dimensional “igloo” of directions for each relative velocity. The actual spacecraft risk calculations are made using these igloos as the basic computational structure.

For a given spacecraft orbit, there exists a unique mapping between any igloo element – the two-dimensional direction bin and the one-dimensional relative speed bin – and any orbital distribution element. The bulk of the ORDEM calculations are made to compute this mapping matrix. Once the mapping matrix is computed, then any orbit distribution file (sorted by year, size, and material type) can be used to compute the flux in each igloo element.

A similar process is used for the telescope mode, where the “igloo” elements are much simpler – basically range bins in a conical radar/telescope beam.

In order to simplify the computation of flux uncertainties, uncertainty in the model orbit population distributions is limited to two forms. The first is termed the “random error,” and is the uncorrelated uncertainty of the population in each orbit element cell. This is primarily due to finite sampling error in the reference populations. In addition, the conversion matrix is computed numerically, and preserves an estimate of the numerical computation error.

The second type of uncertainty is the dominant effect, and is termed the “population error.” This term represents the estimated error in the scaling of the total population due to the limitations of finite sampling of our radar and returned surface data. The process used to fit the data uses treats a subpopulation of the objects as a whole when scaling to the data, so this uncertainty is correlated across a sub-population used to fit the data. Note that the populations (and associated flux calculations) for each population are considered to be uncorrelated with those of other populations, so that the correlated uncertainties only apply across a single population.

These correlated and uncorrelated uncertainties are propagated to the final flux calculations. The computed flux reported for each “igloo” bin for each subpopulation (material type and size bin) has an associated random (uncorrelated) uncertainty and population (correlated) uncertainty. Therefore, if one wishes to calculate the uncertainty in combining the information in each flux bin to arrive at a total flux or other risk calculation, care must be taken in combining the correlated and uncorrelated uncertainties correctly.

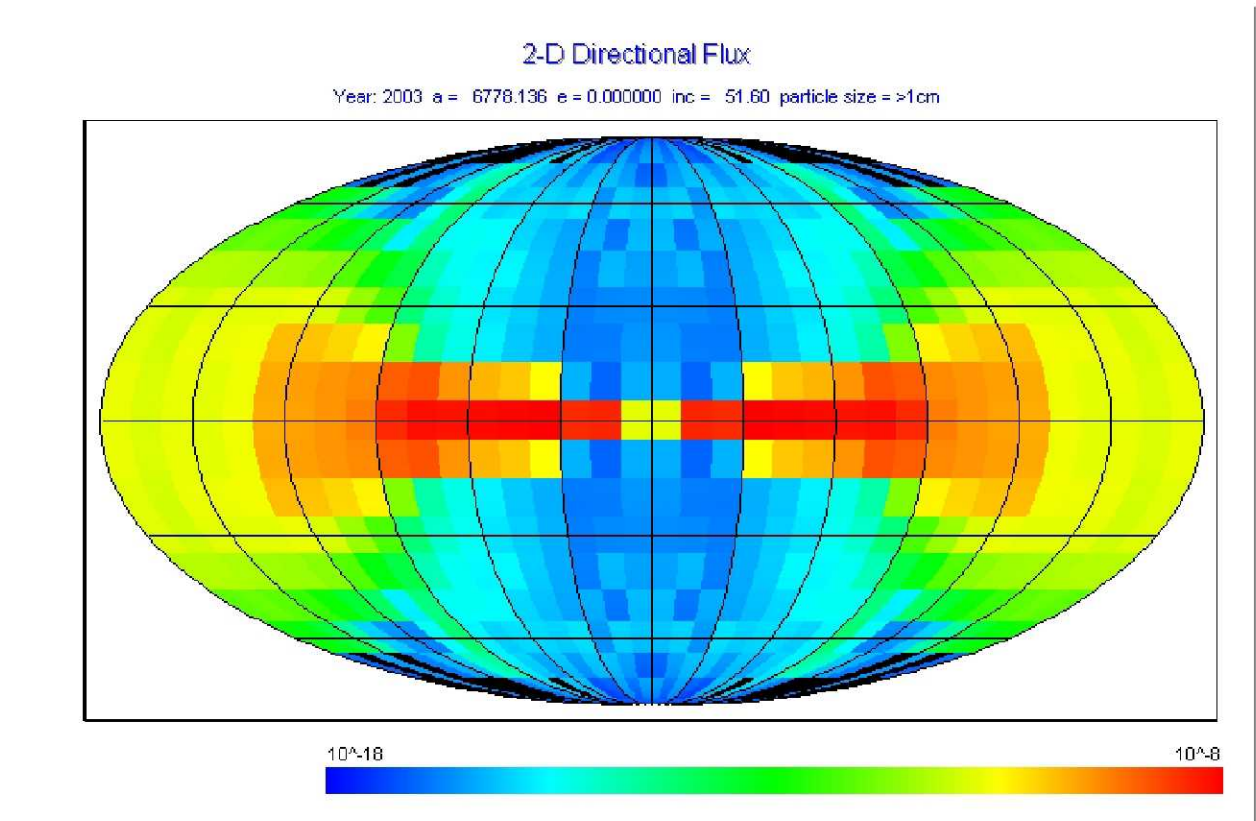


Figure 1. One of the output formats of ORDEM2010 creates Mollweide projections of the orbital debris flux in the spacecraft frame. Each colored box represents an “igloo” direction defined by “yaw/longitude” and “pitch/latitude” relative to the spacecraft direction, defined as the center of the plot. Most of the flux for this orbit can be seen to lie along the “horizontal” plane parallel/tangent to the local Earth surface.

Uncertainties in the material type / mass density distributions are primarily due to our limited data set of examples of material types. The uncertainties for these populations are thus relatively large (as a percentage of the total population) and are of the “correlated” population uncertainty type (they apply across the population of a particular material type). However, the ORDEM2010 uncertainties for these are not considered correlated between populations, so combining the different material into composite total flux numbers have smaller uncertainty values as a percentage of the total population.

There is also built into ORDEM2010 an uncertainty for the future populations that is based on the random nature of future explosions and collisions. The uncertainty is computed on the “spread” of the 100 Monte Carlo LEGEND runs, as each run represents a possible future state of the environment. Note that this uncertainty is only due to the random nature of breakup

phenomena, and does not include changes in future traffic assumptions, variability in future solar activity, or in the possibility of deliberate future breakup events.

CONCLUSION

This paper has presented an overview of NASA's newest orbital debris model, ORDEM2010. While this model has many similarities to previous models, there are a number of new features that greatly expand how it can be used. One is the extension of the regimes covered so the model is no longer limited to low-Earth orbit. This includes contributions from the GEO environment as well as the capability to handle out-of-plane flux calculations appropriate for elliptical or higher altitude orbits. Another important extension is the capability to estimate the uncertainties in the computed fluxes. The inclusion of material properties of the debris population also aids in the computation of spacecraft damage risk. It is our hope that this model will increase our capability to more accurately assess spacecraft orbital debris risk.

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